Circulation in Southern Puget Sound's Finger Inlets: Hammersley, Totten, Budd, Eld, and Case Inlets

Curtis C. Ebbesmeyer
Evans-Hamilton, Inc.

Robert J. Stewart
Digital Analogics, Inc.

Skip Albertson
Washington State Department of Ecology, Environmental Investigations and Laboratory Services Program (EILS)

Introduction

The seven waterways inland of Devils Head hold the southernmost 2% of Puget Sound's water, and open westward so as to resemble a human hand: the thumb represents Case Inlet, and the four fingers correspond to Hammersley, Totten, Eld, and Budd inlets (Figure 1; McLellan 1954). They are thus known as the finger inlets.

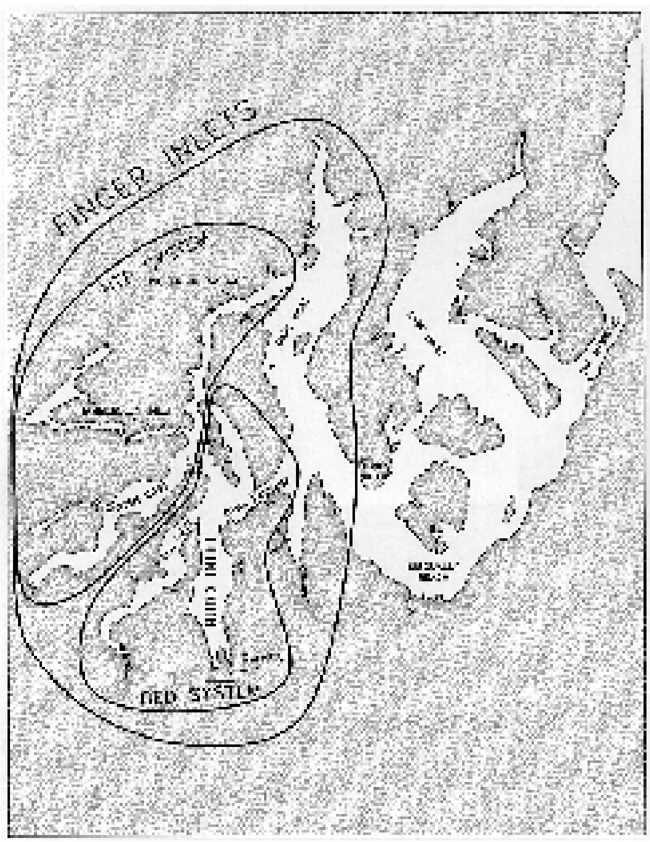

Figure 1. Location of the five finger inlets within Southern Puget Sound. The finger inlets are (named clockwise): Budd Inlet, 2) Eld Inlet, 3) Totten Inlet, 4) Hammersley Inlet, and 5) Case Inlet. The finger inlets are composed of two dynamically distinct groups of water bodies separated by Squaxin Passage: the BED system or group to the east consists of Budd and Eld Inlets and Dana Passage; and the HTP group to the west consists of Hammersley and Totten Inlets and Pickering Passage.

Available oceanographic information has been inadequate, both spatially and temporally, to resolve the relevant oceanographic processes controlling the circulatory exchange amongst the finger inlets. In addition, as new information has been acquired, important physical processes at progressively smaller scales have been uncovered. To discern the exchange between the finger inlets, five widely differing techniques were explored.

The combined techniques led us to subdivide the finger inlets into two dynamically distinct groups (Figure 1): 1) the eastern, or BED group, designating Budd and Eld inlets, joining Case Inlet through Dana Passage; and 2) the western, or HTP group, designating Hammersley and Totten inlets, joining Case Inlet through Pickering Passage. Additional aspects of the analyses may be found in the Budd Inlet Scientific Study (1998) funded by the Lacey, Olympia, Tumwater, Thurston County (LOTT) partnership of municipalities.

Specifically, the five techniques applied were:

1. To discover the transport pathways, drift cards were released monthly during 1996–1997, and recoveries by the public were tabulated.
2. To confirm the limited exchange between the BED and HTP groups inferred from the drift cards, historical hydrographic data were subjected to a Principal Components Analysis (PCA).
3. To confirm that Squaxin Passage blocks the exchange between the BED and HTP groups, dye was injected into a physical model of the tides within the finger inlets.
4. The blockage was also evident from contrasting the temperature, salinity, and density at both ends of Squaxin Passage.
5. Differences between the water masses discharged by the BED and HTP groups into Case Inlet were inspected by a high-resolution conductivity-temperature-depth transect (CTD; 2-km station spacing).

1. Drift Cards

Drift cards provided the clearest evidence of finger inlet behavior. Before this study, however, few drifting objects (bottles, cards) had been deployed in Southern Puget Sound. To rectify this situation, 9,950 drift cards were deployed. The cards are wooden, measure approximately 3" x 5", and were coated with orange, non-toxic paint to render them readily visible to beachcombers. Each card carried a serial number preceded by 'L' for LOTT, an address, and an 800-telephone number enabling beachcombers to easily report recoveries. The reports were tabulated within 1-mi shoreline segments because most of the cards were found along short stretches of beach in the vicinity of dynamical boundaries.

Fifty cards were released at 15 sites in Budd Inlet, totaling 750 cards during a single day and 8,950 cards summed over the 12 cruises during 1996–1997 (Table 1; Figure 2; encountering a floating dead body prevented 50 cards from being released during Drop 5 at Site 4 on February 11, 1997). The boat drops were made during monthly CTD surveys and were not coordinated with respect to winds or tides.

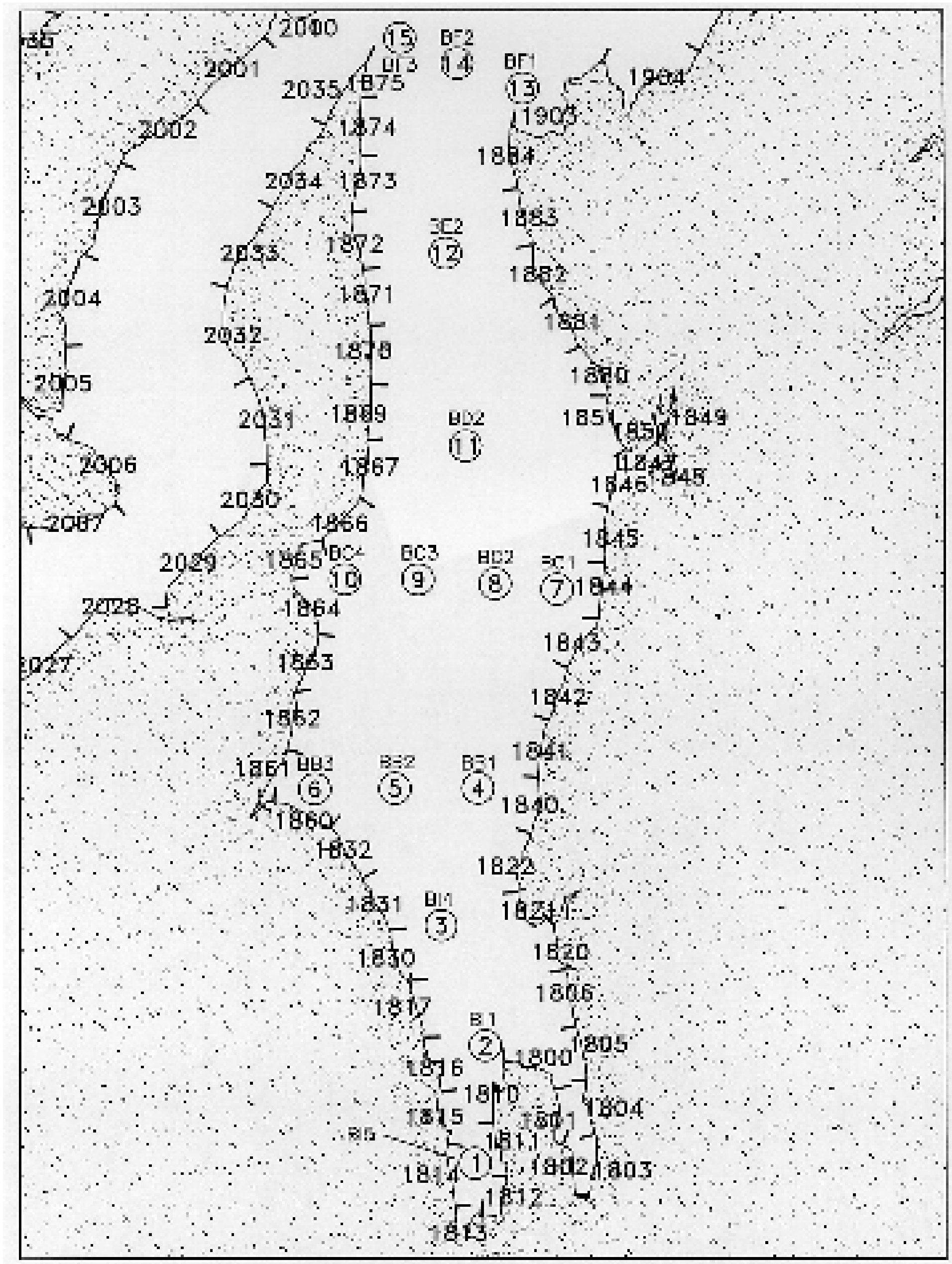

Figure 2. Monthly drift card release sites in Budd Inlet. Circled numbers 1–15 indicate drift card drop sites, numbers between ticks along the shore indicate 0.25-mi long segments in which drift cards were tabulated.

After a few drops, we noticed that very few cards drifted from Budd Inlet to Eld, Totten, and Hammersley Inlets and Pickering Passage. We questioned whether enough beachcombers were there to report cards. Therefore, on January 22, 1997, from a Cessna 172 light aircraft flying at 500-ft altitude, 16 batches of 50 cards were dropped within half an hour along the central axes of the Budd, Eld, Totten, and Hammersley Inlets, and another four batches along Pickering Passage (Figure 3). To maximize the time the cards drifted within the five water bodies, thereby providing beachcombers optimal recovery opportunities, the cards were air-dropped on a flood tide.

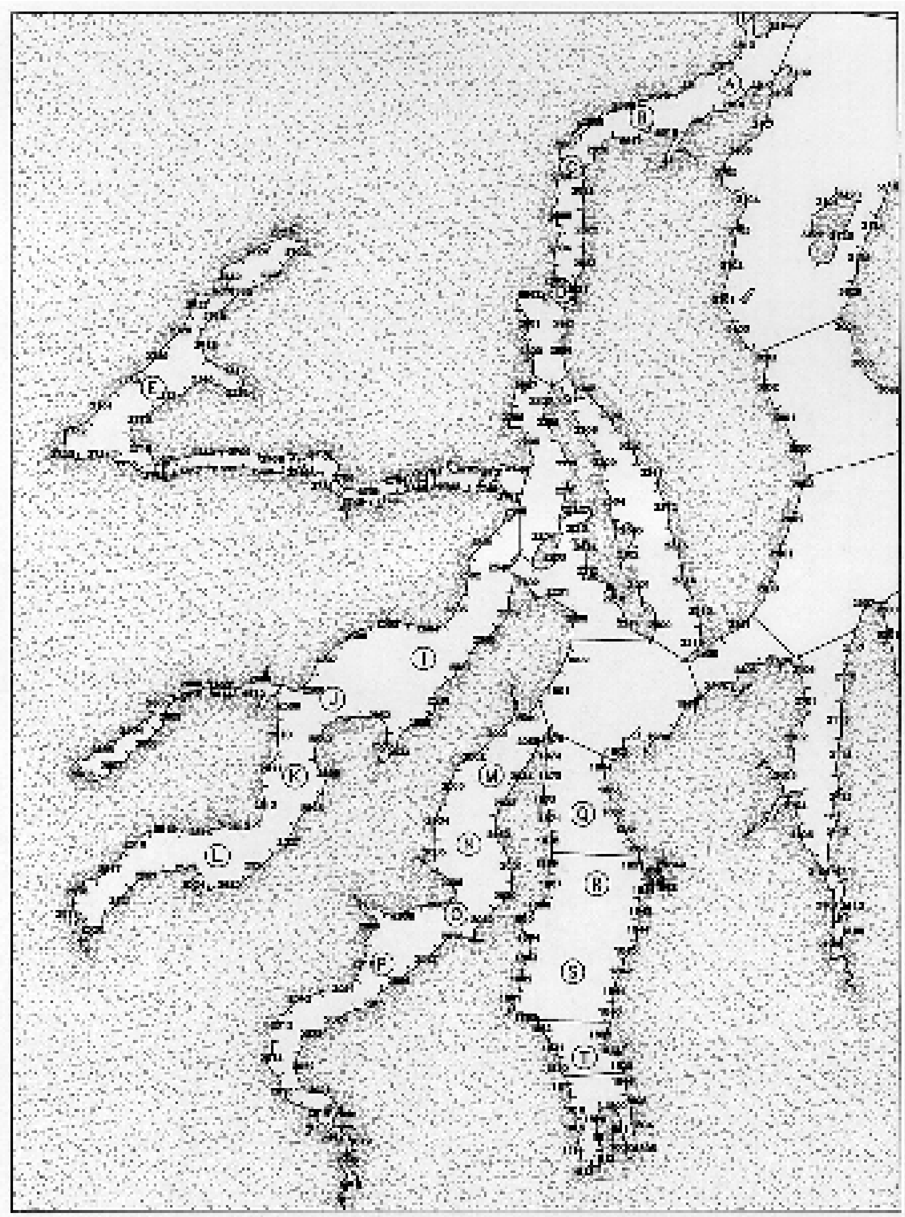

Figure 3. Air-drop drift card release sites. Twenty sites where drift cards were released on January 22, 1997 from a small aircraft: sites A–D in Pickering Passage; sites E–H in Hammersley Inlet; Sites I–L in Totten Inlet; sites M–P in Eld Inlet; and sites Q–T in Budd Inlet. Numbers between ticks along the shore indicate segments in which drift cards were tabulated.

All totaled, beachcombers reported 51% of the Budd Inlet drops as of January 14, 1998, when the tabulations were terminated to meet reporting deadlines. The percentages recovered from the air-drops were comparable for each inlet (sites are shown in Figure 3): 51.5%, Pickering Passage (Sites A–D); 42.5%, Hammersley Inlet (Sites E–H); 55.0%, Totten Inlet (Sites I–L); 35.5%, Eld Inlet (Sites M–P); and 49.5%, Budd Inlet (Sites Q–T). Therefore, adequate numbers of walkers combed the beaches around each of the finger inlets.

Table 1. Drift Card Releases in Budd Inleta

Drop number	Date	Number of cards released
1	October 2, 1996	750
2	November 6, 1996	750
3	December 5, 1996	750
4	January 8, 1997	750
5	February 11, 1997	750
6	March 19, 1997	750
7	April 16, 1997	750
8	May 7, 1997	750
9	June 11, 1997	750
10	July 21, 1997	750
11	August 20, 1997	750
12	September 30, 1997	750
12 cruises		8,950 cards released

* Drop-site locations are displayed in Figure 2.

Of the 8,950 cards released in Budd Inlet, only 7.3% of the recoveries occurred west of Squaxin Passage, 6.0% of which came from upper Case Inlet (Figure 4). Three out of four recoveries (75.9%) were found either in Budd Inlet (31.0%) or exited through Dana Passage (44.9%). Of the 400 cards air-dropped in Hammersley and Totten Inlets, the bulk (43.6%) were found in the inlets themselves, and 20.0% exited through Dana Passage with 8.7% found in upper Case Inlet (Figure 5). These results suggest that Squaxin Passage blocks cards drifting westward from Budd Inlet, but allows a substantially greater fraction to pass eastward through Dana Passage (Figures 4 and 5).

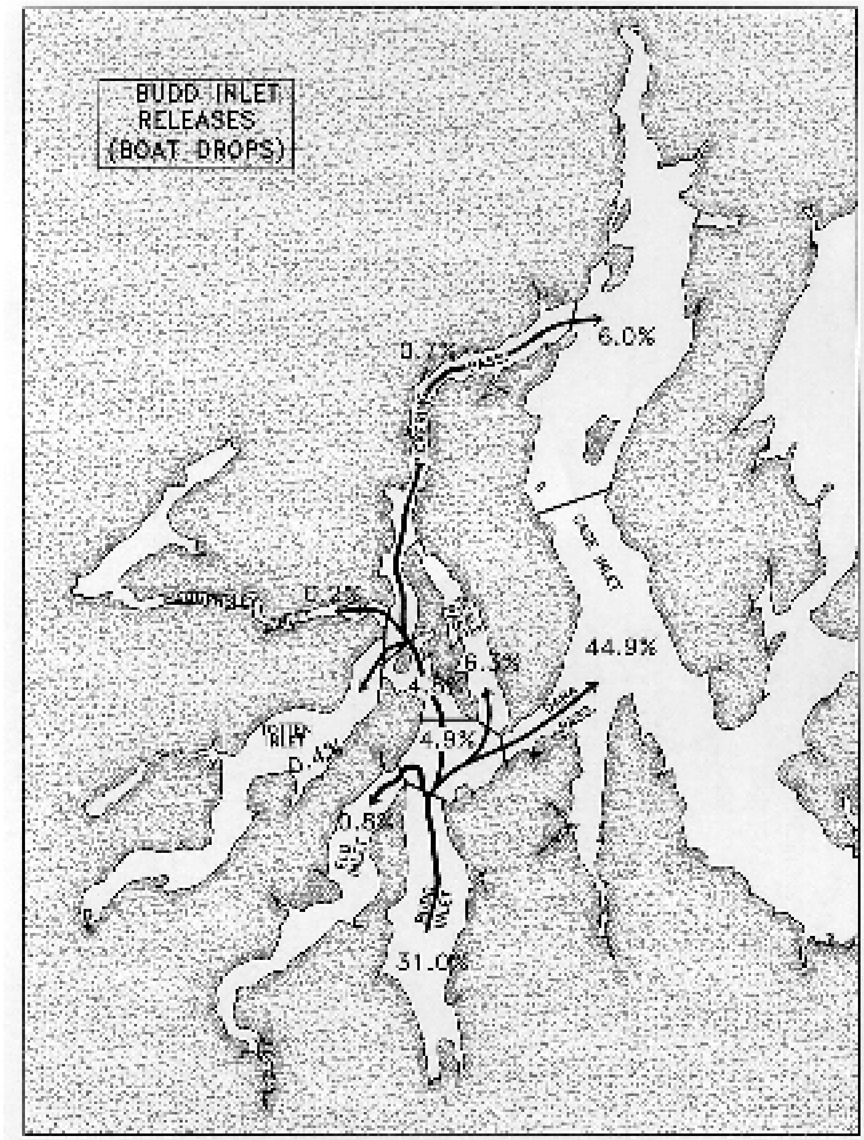

Figure 4. Drift card pathways from Budd Inlet. Shown are percentages of the total number of cards recovered (4,609) from 8,950 total cards released in Budd Inlet from October 1996 through September 1997 (see Table 1 and Fig. 1 for release dates and locations). Lines represent divisions between water bodies. Most cards were either found in Budd Inlet (31.0%) or exited through Dana Passage into Case Inlet (44.9%), whereas a smaller percentage traveled via Squaxin (4.8%) and Pickering (0.7%) passages to reach upper Case Inlet (6.0%). Very few cards were found in Eld (0.8%), Totten (0.4%), and Hammersley (0.2%) Inlets.

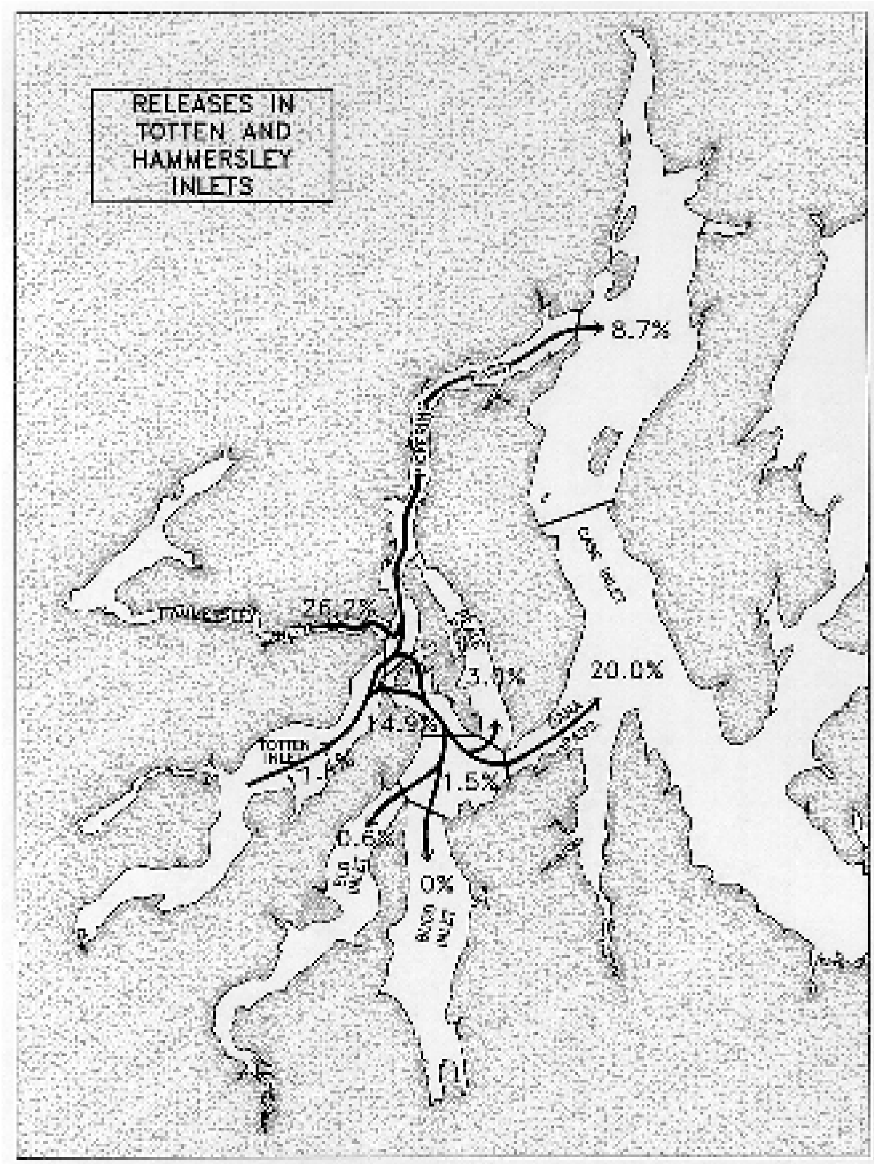

Figure 5. Drift card pathways from Totten and Hammersley Inlets. Shown are percentages of the total number of cards recovered (195) from 400 total cards air-dropped in Totten and Hammersley Inlets on 22 January 1997 (see Fig. 3 for locations). Lines represent divisions between water bodies. Most cards were either found in Totten and Hammersley Inlets (43.5%) or exited through Pickering Passage into upper Case Inlet (8.7%), whereas a smaller percentage travelled via Squaxin (14.9%) and Dana passages to reach lower Case Inlet (20.0%). Very few cards were found in Eld (0.6%) or Budd (none) Inlets.

Tabulations in the shoreline segments pinpointed the blockage within Squaxin Passage (Figure 6). Of the 234 cards recovered in Squaxin Passage and approaches, 11% were found to the west and 89% to the east of Hope Island. Of the latter category, most came from three embayments along the western shores of Squaxin Island.

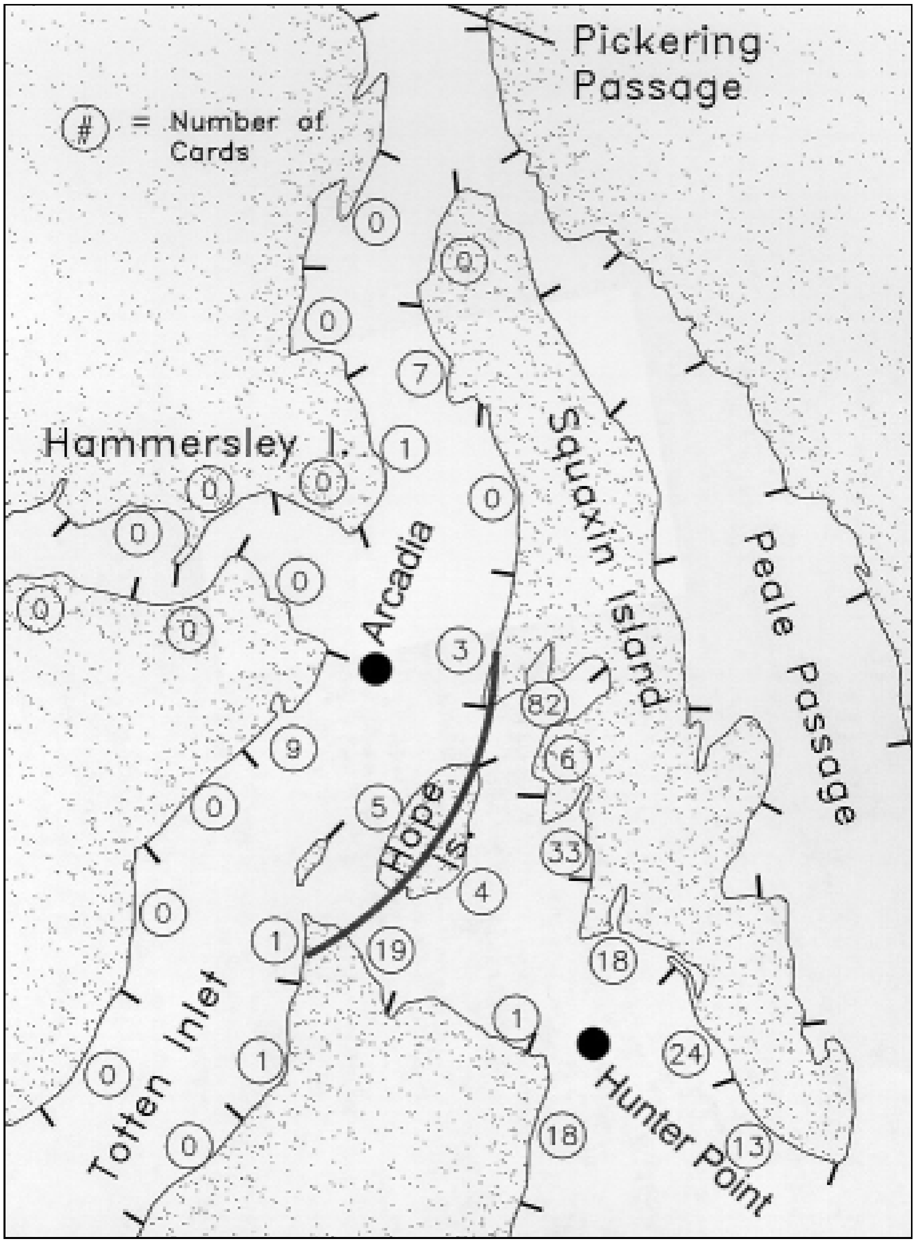

Figure 6. Drift card recoveries in Squaxin Passage. Of the 234 cards released in Budd Inlet and recovered in the shoreline segments in Squaxin Passage, as shown here, 90% were found east of Hope Island and 10% to the west. The thick solid line represents the dynamical blockage between the BED and HTP groups of finger inlets, and the two dots show the locations where water properties were contrasted between the east (Hunter Point) and west (Arcadia) ends of Squaxin Passage.

To examine how the cards exited the BED and HTP groups into Case Inlet, drift card recoveries were tabulated as histograms within 40 slices from the head of Case Inlet through Nisqually Reach (Figures 7 and 8). Differences between the groups became evident by contrasting the histograms from four drift card releases (Figure 8a–8d): a) 8,950 cards boat-dropped in Budd Inlet, b) 400 cards air-dropped in Eld and Budd inlets, c) 200 cards air-dropped in Pickering Passage, and d) 400 cards air-dropped in Totten and Hammersley inlets.

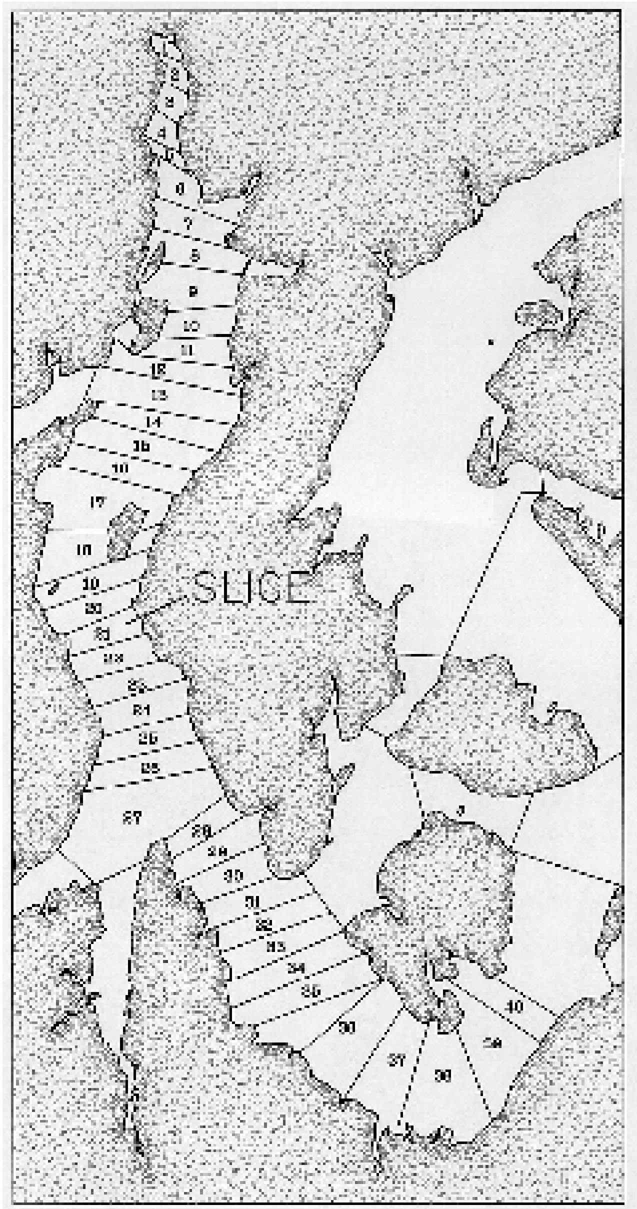

Figure 7. Forty slices along Case Inlet between Nisqually reach and the head of Case

These histograms showed that the cards accumulated in two modes along Case Inlet in the vicinity of the discharges from Dana and Pickering passages. Because of the modal separation along Case Inlet, the drift card recovery maps shown in Figures 4 and 5 were constructed assuming no exchange between the slices of upper Case Inlet (slices 1–19) and lower Case Inlet (slices 20–40).

2. Principal Component Analysis

Principal component analysis (PCA) is a statistical procedure that combines various parameters into groups that explain maximal amounts of environmental variability. To conduct the PCA, precipitation and river runoff were compared with historical salinity measurements. In the late 1950s, to address concerns that pulp mill effluents were affecting oyster harvests, the finger inlets were surveyed by the University of Washington (UW) (Olcay, 1959), ITT-Rayonier Corporation (ITT, unpubl. data), and the Washington State Department of Fisheries (unpubl. data).

Fifteen cruises were selected for the PCA by culling the best quality, most extensive data available during 1957–1958 (see Olcay, 1959). The ITT data were used to estimate values missing in the UW data for Hammersley Inlet during spring and summer 1957. River discharge into Budd Inlet was estimated using historical data from the U.S. Geological Survey (USGS) gauge on the Deschutes River at Mt. Rainier near McKenna. Runoff for the HTP group was represented by the USGS gauge on Goldsborough Creek. Rainfall onto Budd Inlet was derived from data at Olympia Airport, and for the the HTP group from the Cooperative Weather Station in Shelton.

The first principal component explained 56% of the total variance and represents the signals' annual variation. The second component, accounting for 27%, is the response of the inlets to freshwater inputs. The third component, equalling 5%, represents the difference in inlets' response to rainfall versus runoff.

The PCA component scores showed that the BED and HTP group responses are distinctly different (Figure 9). The variations in salinity at Shelton (SH and sh, Figure 9) are most similar to those at Arcadia and in Totten Inlet (AR, ar, TN, tn). These HTP inlets respond to rainfall in preference to the river runoff. Note also that the salinity variations in the BED inlets tend to be inversely coupled to freshwater inputs. That is, salinity values increase in response to increased fresh water in the lower layers of Case Inlet, Budd Inlet, and Dana Passage, and in the northern portion of Pickering Passage.

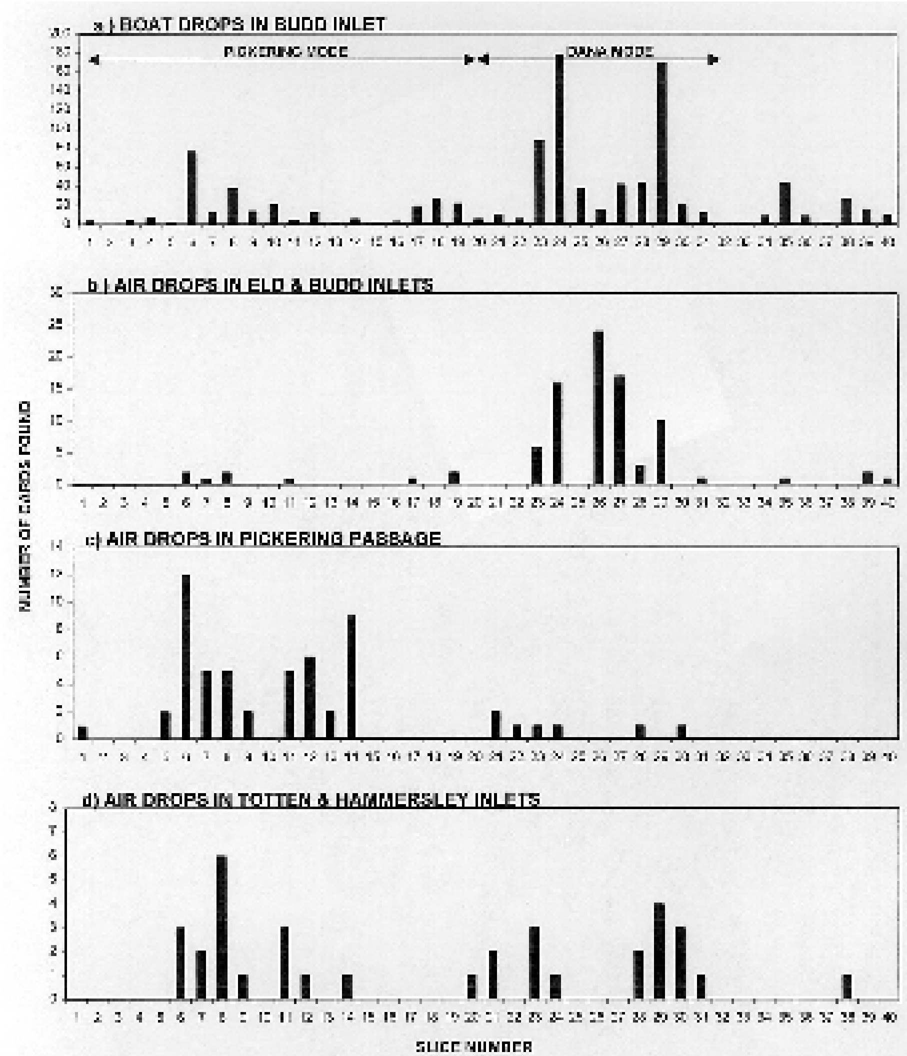

Figure 8. Histograms of drift card recoveries along Case Inlet and Nisqually Reach. a) drift cards found from the 8,950 cards released in Budd Inlet; b) number of cards found from the 400 cards air dropped into Eld and Budd inlets (BED system); c) number of cards found from the 200 air-dropped into Pickering Passage (HTP system); and d) number of cards found from the 400 air-dropped into Totten and Hammersley inlets. The slice numbers begin at the head of Case Inlet and end off Nisqually Reach (Figure 7). Histogram groupings between slice numbers 1–19 correspond to cards from Pickering Passage, and between slice numbers 20–31 from Dana Passage.

The fact that the HTP group displays a different response is not proof that it is decoupled from the BED system. At the very least, the PCA suggests that the two groups are dynamically distinct. Further, the transport between them through Squaxin Passage is not so large as to mask these distinctions.

3. Physical Model

A hydraulic model was constructed at Shoreline Community College to simulate the tides in the finger inlets. Horizontal and vertical scales equalled approximately 196:1 and 11.4:1, respectively. There were no inputs of fresh water. Water flux through Squaxin Passage was examined by staining Totten Inlet with green and Budd Inlet with red dye. Sequences of photos through tidal days showed the relative behavior of the BED and HTP groups.

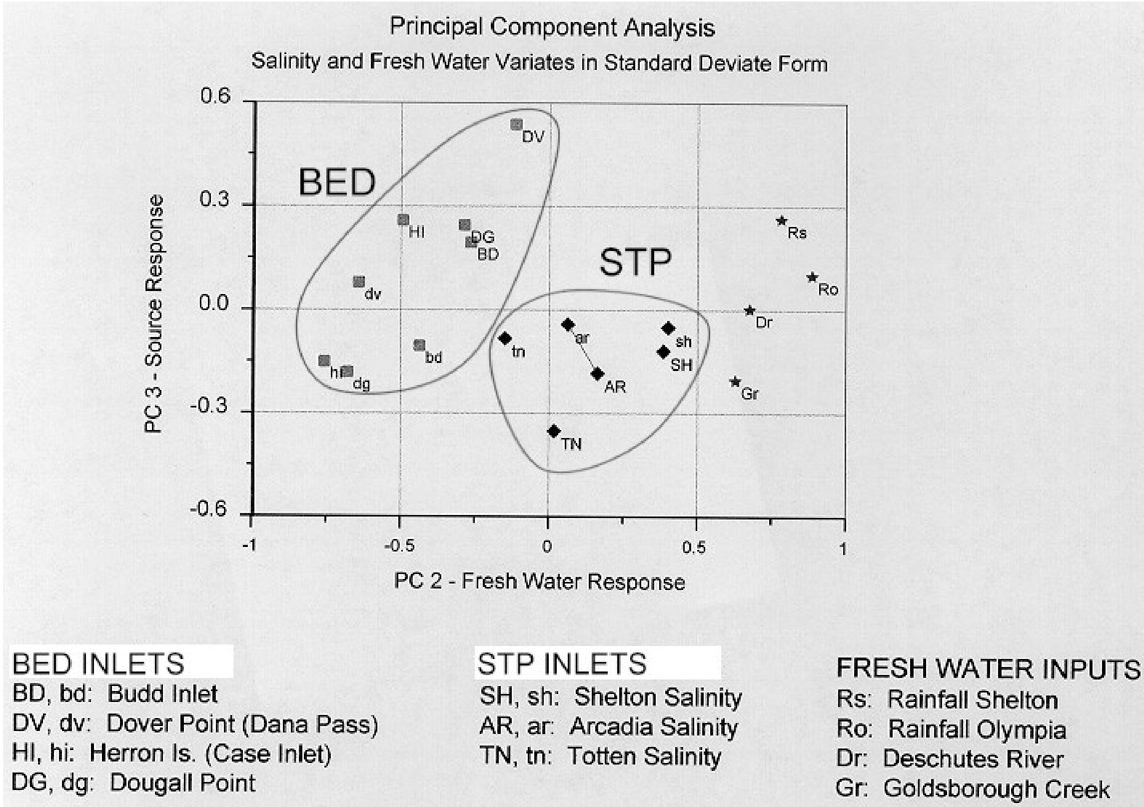

Figure 9. Principal component analysis. Clusters of points corresponding to the BED or eastern groups of inlets, and the HTP or western inlets, have been circled.

After several tidal cycles, the green dye worked its way northward through Pickering Passage entering upper Case Inlet. Small amounts of green dye flowed southward into Peale Passage, with a minor fraction moving toward Budd Inlet. The red dye traveled towards and through Dana Passage, filling lower Case Inlet. Some red dye entered Peale Passage. Repeated simulations revealed no red dye entering the Totten, Hammersley, Pickering system, though dye from that system occasionally was transported toward Budd and exited Dana Passage.

4. Blockage in Squaxin Passage

If Squaxin Passage does block the flow between the BED and HTP groups, the water properties at the Passage's extremities should differ. To explore this hypothesis, temperature, salinity and density at 0 and 10 m depths at west (Arcadia Station) and east (Hunter Point Station) ends of Squaxin Passage were compared (Figure 6). It can be seen in Figures 10 and 11 that, through the water column, water is always more dense at the east than at the western end of Squaxin Passage. The density difference averages one sigma-t unit, a substantial value in the context of other Puget Sound water bodies. The density difference occurs because the waters west of Squaxin Passage are almost always warmer and fresher than those to the east.

In the absence of a dynamical mechanism, higher density water normally flows into regions of lower density. Though the dynamical nature of the Squaxin blockage remains unknown, there can be little doubt that it does separate the BED and HTP groups.

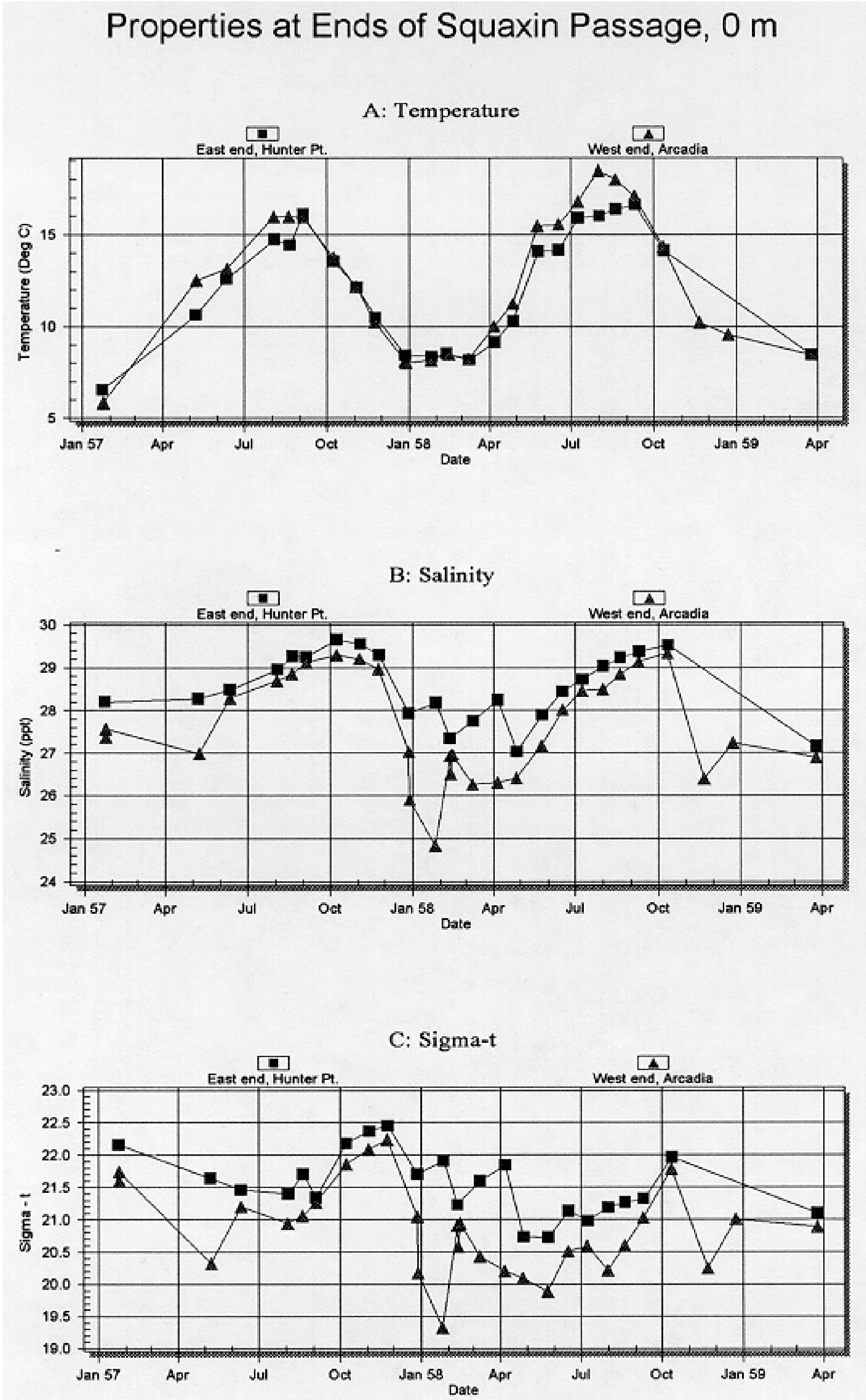

Figure 10. Water contrast across Squaxin Passage at the sea surface. The differences across Squaxin Passage were represented by temperature (a), salinity (b) and density (c; sigma-t units) observed at Hunter Point representing BED System and Arcadia representing the HTP System. Note that the HTP waters are almost always fresher, warmer and less dense than those in the BED group.

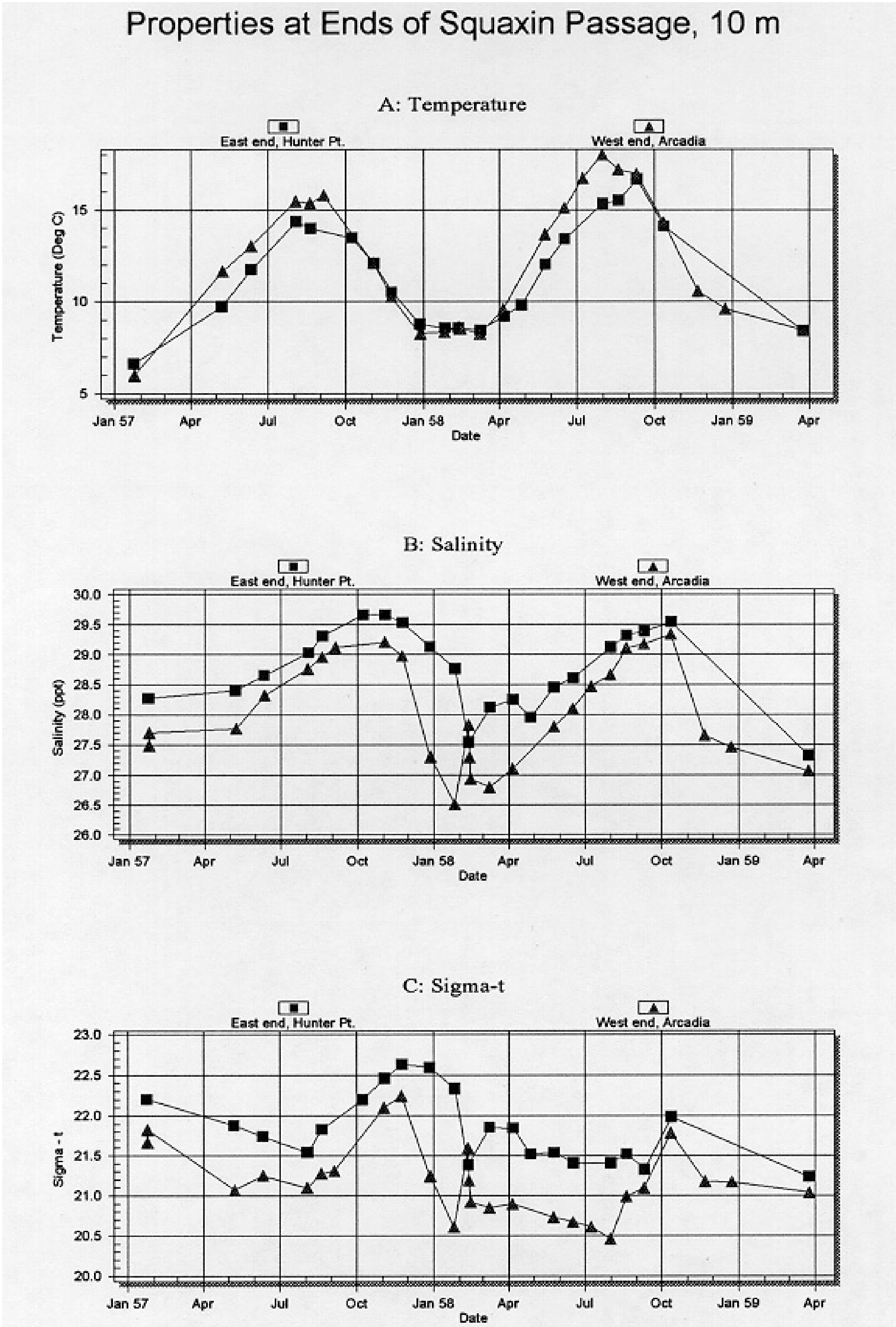

Figure 11. Water contrast across Squaxin Passage at 10-m depth. The difference across Squaxin Passage were represented by temperature (a), salinity (b) and density (c; sigma-t units) observed at Hunter Point representing BED System and Arcadia representing the HTP System. Note that the HTP waters are almost always fresher, warmer and less dense than those in the BED group.

5. Case Inlet High-Resolution CTD Transect

The BED and HTP groups discharge via Dana and Pickering Passages into lower and upper Case Inlet, respectively. Based on the foregoing analyses, we hypothesized that the differences between BED and HTP effluents would be reflected in Case Inlet's water mass structure. Prior to this time, however, Case Inlet water properties had been sampled at widely spaced intervals (~ 5 km; Collias et al., 1974). To obtain a resolution comparable to that of the drift card histograms, 19 CTD profiles were taken at 2-km intervals from the Nisqually River to the head of Case Inlet (Figures 12–17).

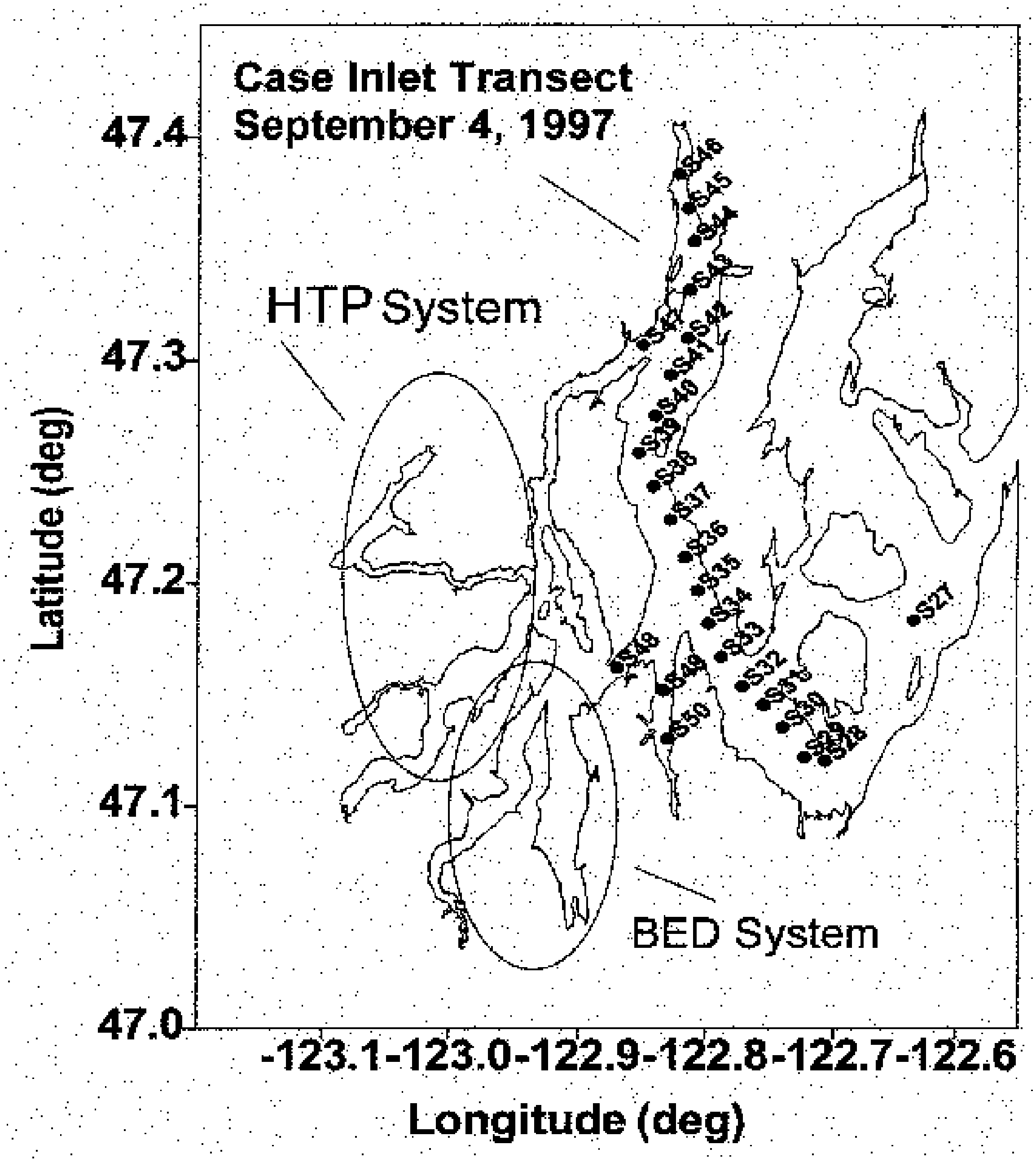

Figure 12. Case Inlet high-resolution transect. On September 4, 1997 CTD profiles were obtained from the Research Vessel Barnes at 19 stations spaced about 1 mi apart, from off the mouth of the Nisqually River on the south to the head of Case Inlet on the north.

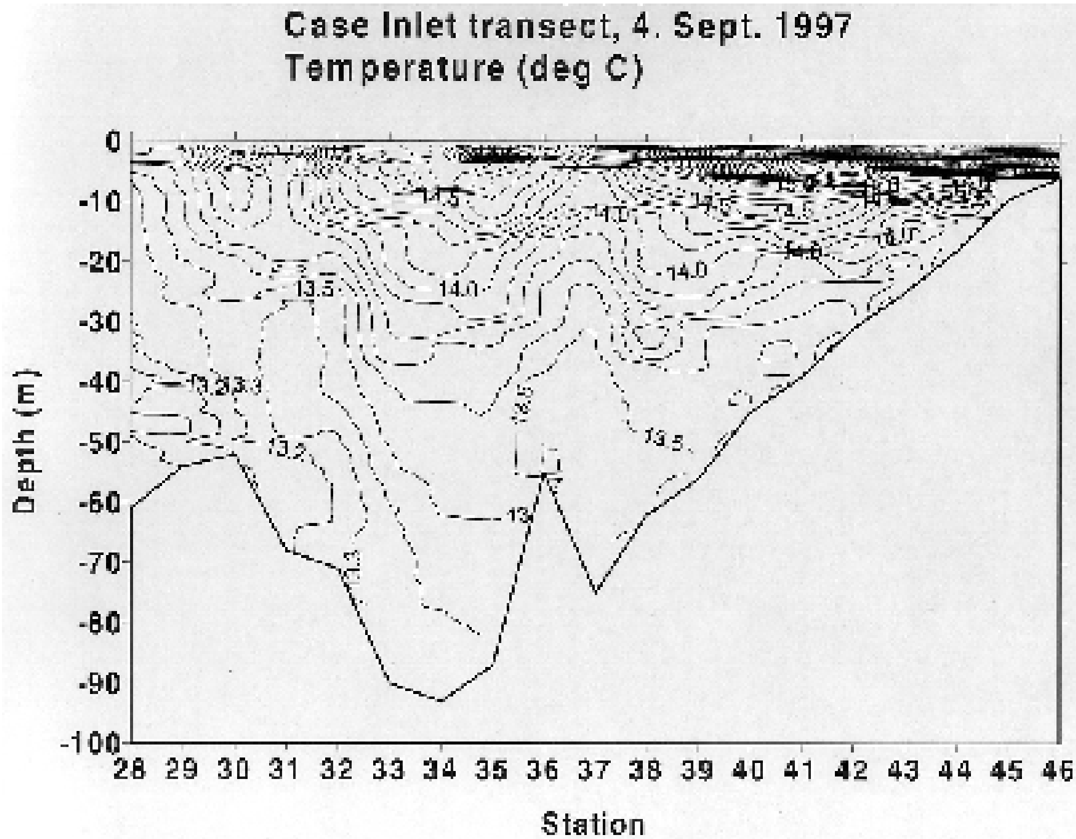

Figure 13. Case Inlet high-resolution transect: temperature contours.

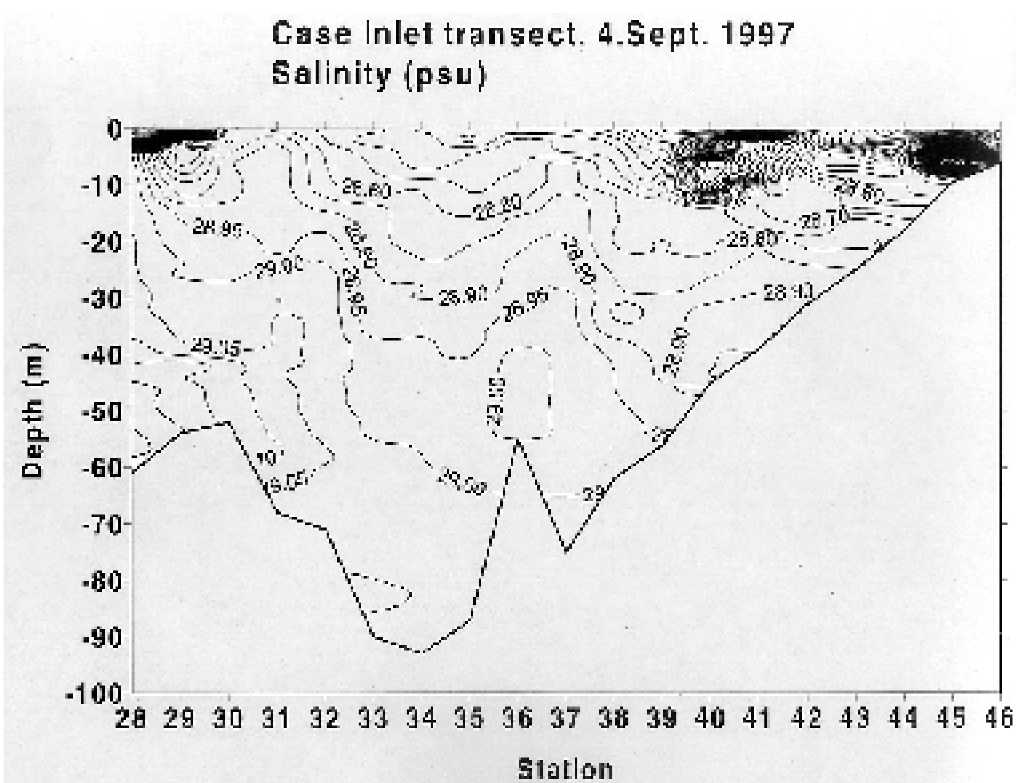

Figure 14. Case Inlet high-resolution transect: salinity contours.

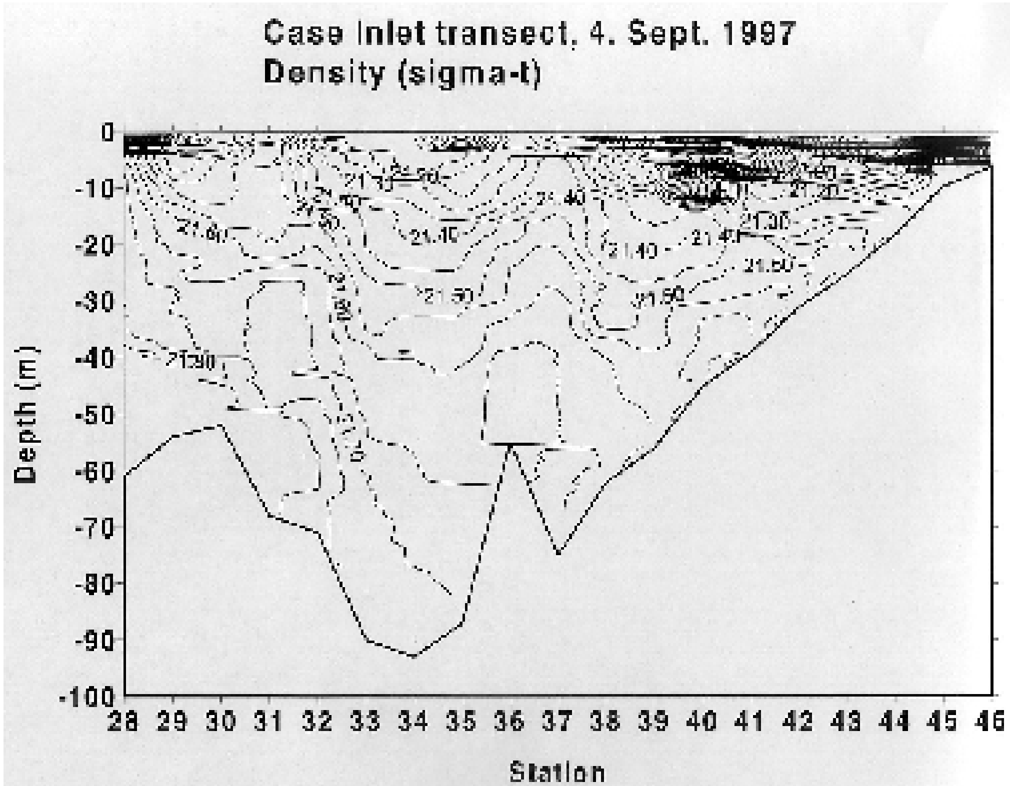

Figure 15. Case Inlet high-resolution transect: density contours (sigma-t units).

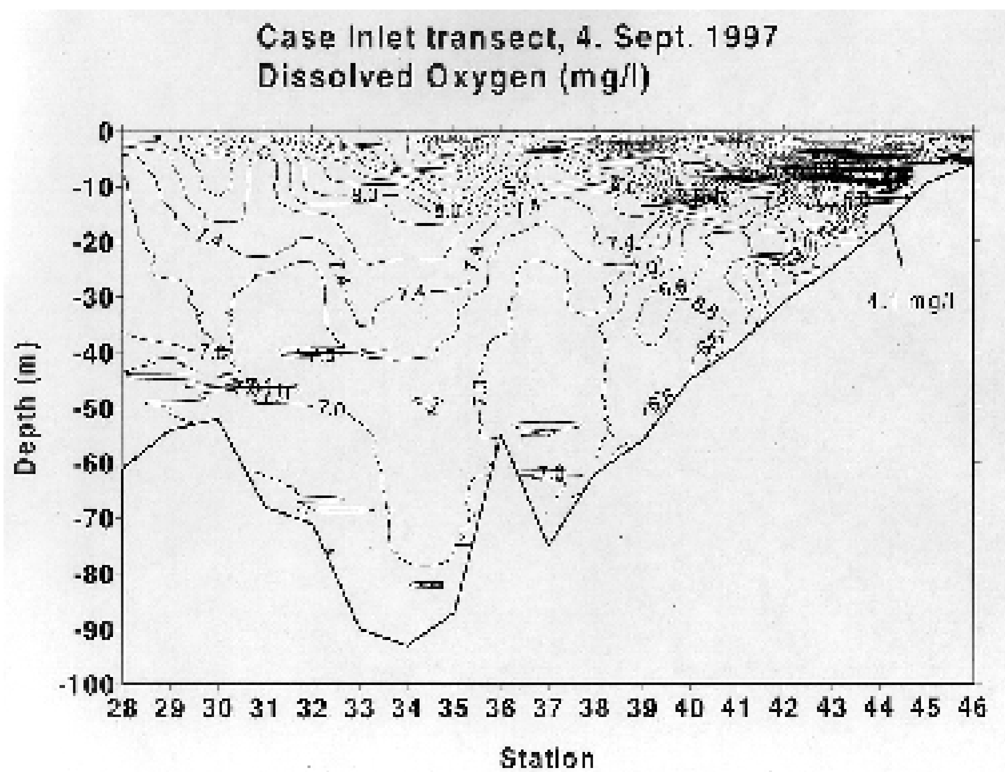

Figure 16. Case Inlet high-resolution transect: dissolved oxygen contours.

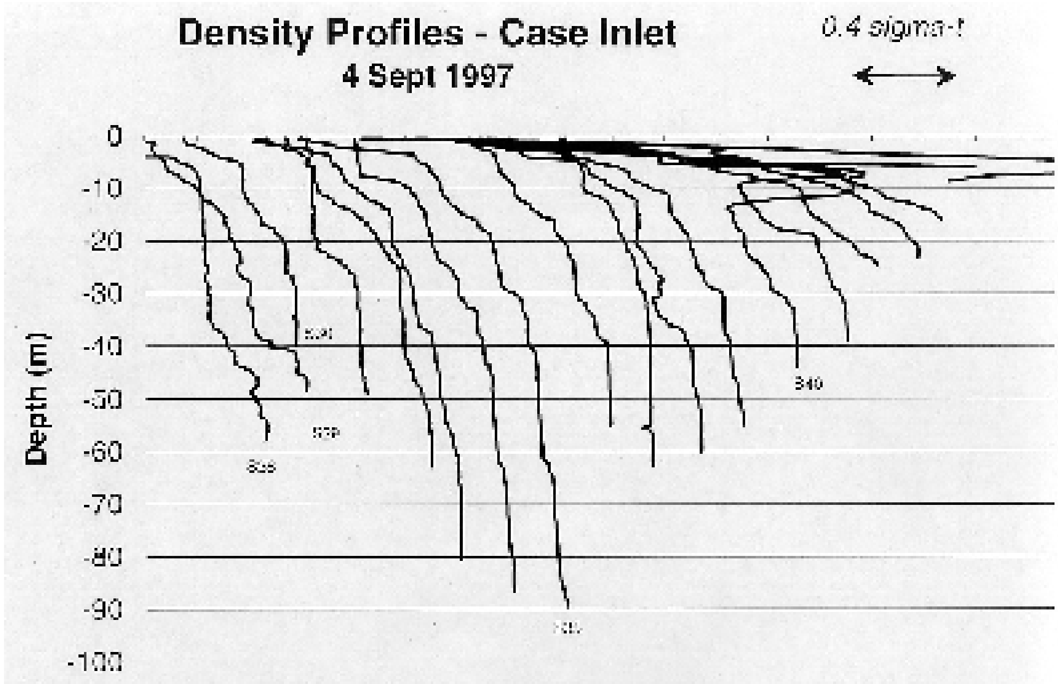

Figure 17. Case Inlet high-resolution transect: density profiles.

Contours of temperature and salinity (Figures 13, 14) showed relatively warm, saline water parcels, measuring ~2 km in horizontal extent, exiting from Pickering Passage. Because their density equaled that of the deepest water, these parcels probably sank to Case Inlet's greatest depths. Toward the end of summer, warm air temperatures apparently evaporate more fresh water than precipitation and runoff supply. This produces high salinities, especially in the Totten and Little Skookum inlets.

Density profiles in Case Inlet indicate regions of homogeneous water separated from one another by sharp gradients, a lenticular structure reminiscent of Puget Sound's Main Basin where discrete water parcels are produced by intense vertical mixing in The Narrows (Figures 15 and17). The parcels in Case Inlet are likely produced by strong tidal mixing in Dana Passage.

To delineate between the origin of different water masses, data from all depths were plotted on a temperature-salinity (T-S) diagram (Figure 18). The deep-water end point at the Nisqually station (28), while having the coldest value on the T-S diagram, has a density nearly equal to those at stations 40 and 45 (nearly 22 sigma-t units). Surprisingly, the maximum densities at stations 40 and 45 are at intermediate depths and, because they are denser than surrounding water, identify sinking water masses. Since the temperature at stations 40 and 45 monotonically decreases with depth, the high density is due to a subsurface salinity maximum. Therefore, at the time of this cruise it was apparent that these anomalously dense water masses were being formed by evaporation in the HTP group. Station 40, south of Pickering Passage in Case Inlet, was sampled on an ebbing tide, whereas station 45, north of the passage, was sampled on a flood. We presume that tidal advection accounts for these multiple encounters of saline Pickering water.

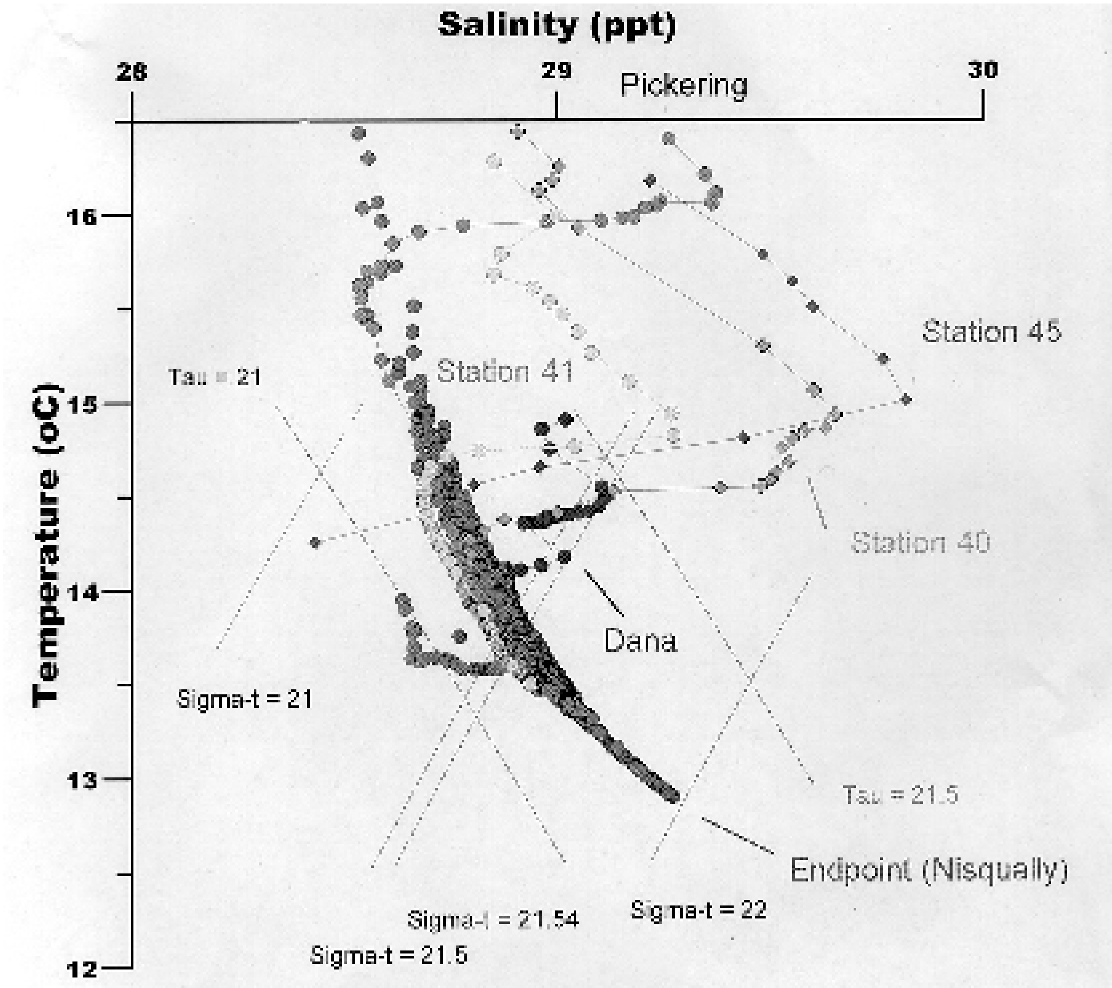

Figure 18. Temperature-salinity diagram for high-resolution survey.

The bulk of the temperature and salinity points lay parallel to lines of constant spiciness (tau), which indicates that these points are insulated against sources and sinks of spiciness (heat and salt). The individual CTD casts (stations 40, 41, 45, and 48) joined by continuous lines on the T-S diagram, that repeatedly cross lines of constant density occur at locations where water masses are either rising or sinking.

The high-resolution survey showed Case Inlet's water mass structure as follows (Figure 19): a) plume of diluted Nisqually River water; b) dense water intruding over the sill (c) off the Nisqually River delta; d) net outflowing layer above the depth of no-net-motion (e) at approximately 20 m; f) net inflow of deep water into Case Inlet; g) parcel of dense water detached from the main mass of intruding water (b); h) Dana Passage cross-section; i) water parcel upwelled along vertical arrow into the surface waters of Dana Passage; j) parcels of water formed in the HTP system and ejected from Pickering Passage poised to sink to the bottom of Case Inlet; k) parcel of water formed in the BED system; l) densest water at bottom of Case Inlet; and m) a zone of depressed dissolved oxygen concentration (Figure 16).

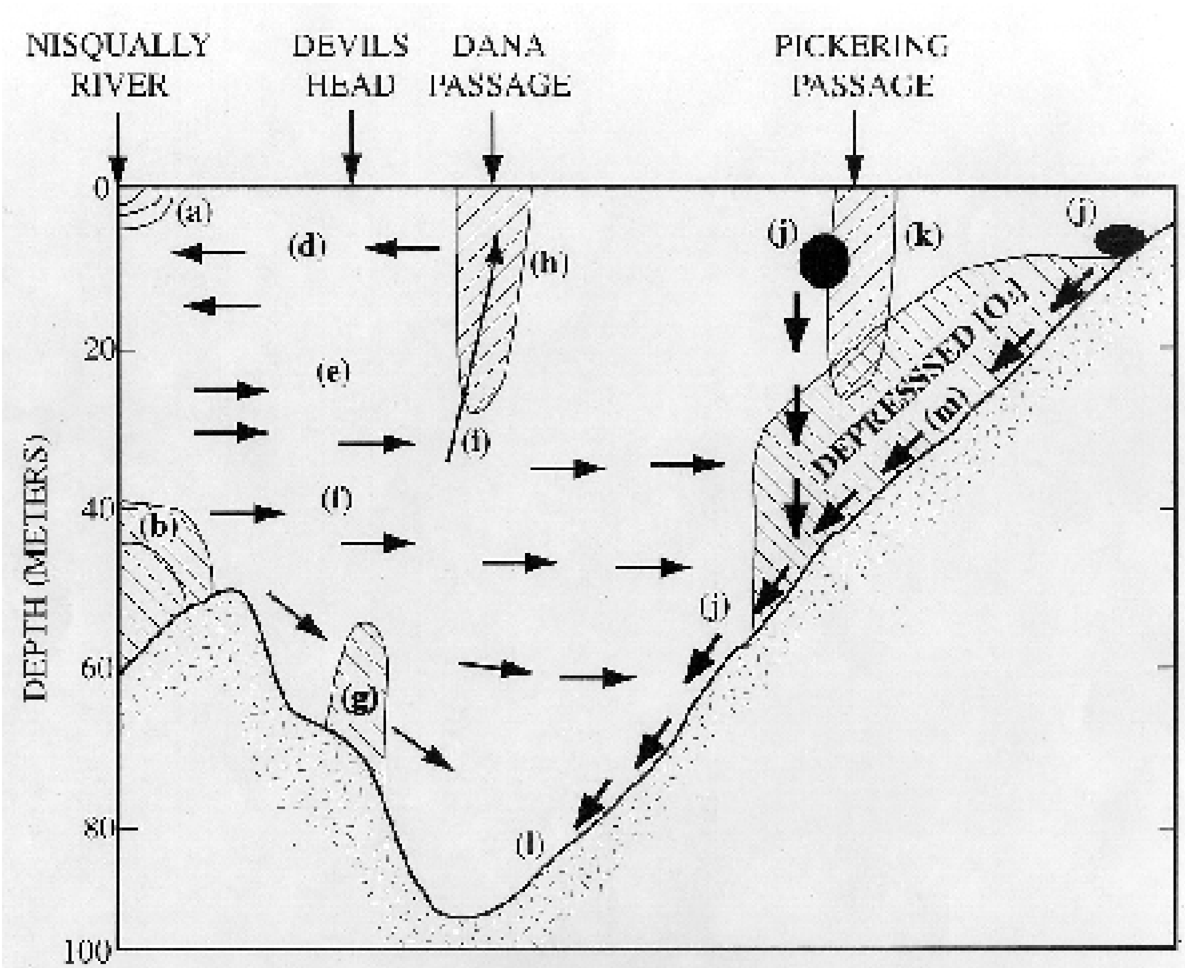

Figure 19. Case Inlet schematic water structure from the Nisqually River (left) to the head of Case Inlet (right). Based on observations of temperature, salinity, density and dissolved oxygen made on September 4, 1997, the schematic was derived with the following elements: (a) plume of diluted Nisqually River water; (b) dense water intruding over the sill (c) off the Nisqually River delta [below (a)]; (d) net outflowing layer above the depth of not-net-motion (e) at approximately 20 m depth; (f) net inflow of deep water into Case Inlet; (g) parcel of dense water detached from the main mass of intruding water (b); (h) Dana Passage cross section; (i) water parcel upwelled along vertical arrow into the surface waters of Dana Passage; (j) parcels of dense water formed in the HTP group and ejected from Pickering Passage (k) poised to sink to the bottom of Case Inlet at l, densest water at bottom of Case Inlet equals 21.7 sigma-t units; (m), zone of depressed dissolved oxygen.

Conclusions

The five analytical approaches (drift cards, PCA, physical model, historical water properties, high-resolution survey) support one another in revealing a unique collective behavior to the water circulation in the finger inlets west of Devils Head. From them, Southern Puget Sound's finger inlets may be grouped into the BED and HTP groups which discharge differing water masses into Case Inlet, including: 1) lenses of salty HTP water spilling from Pickering Passage into Case Inlet; 2 and 3) shallow surface plumes extending from the head of Case Inlet and from the Nisqually River; 4) well-mixed BED effluent from Dana Passage separating the freshwater plumes; and 5) denser Southern Puget Sound water intruding over the Nisqually Reach sill.

The tides are instrumental in flushing the finger inlets, but the details differ between the western and eastern inlets. For Budd and Eld inlets, the deep waters lying off the mouth of Dana Passage are closely linked by the mixing in Dana Passage, and periods of high river runoff may lead to enhanced transport in the Devils Head and Gordon Point reaches, which paradoxically appears to enhance the flow of deep salty water into the region. The HTP group does is not closely coupled to this deep water in the same fashion as at the BED group, which flushes primarily through Pickering Passage, the primary modulation to their tidal transport being associated with rainfall.

Determining why Squaxin Passage blocks the exchange between the BED and HTP groups will require detailed, local hydrographic, current meter, and hydrodynamical modelling studies.

Acknowledgements

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